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Updated Report Acceleration of Polarized Protons to 120-150 GeV/c at Fermilab

SPIN@FERMI Collaboration
Michigan, Fermilab, Jefferson Lab,
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IHEP-Protvino, Novosibirsk

The SPIN@FERMI collaboration has updated its 1991-95 Reports on the acceleration of polarized protons in Fermilab's Main Injector, which was commissioned by Fermilab. This Updated Report summarizes some updated Physics Goals for a 120-150 GeV/c polarized proton beam. It also contains an updated discussion of the Modifications and Hardware needed for a polarized beam in the Main Injector, along with an updated Schedule and Budget. For reference, also attached to the e-mail containing this Updated Report are reprints of the 1992 and 1995 Reports on Polarized Beams at Fermilab by our SPIN collaboration.

Some highlights of the Update are:

- Two superconducting Siberian snakes in the Main Injector, one superconducting 60° rotator in the 120-150 GeV/c extraction line, a 4% partial warm solenoidal Siberian snake in the 8.9 GeV/c Booster (oscillating with the Booster frequency) and some other minor hardware should allow about 75% polarization to be maintained and manipulated in the RFQ, Linac, Booster, Recycler Ring and Main Injector, and then extracted to the experiments (See Fig. 1.9).
- Polarized ion sources now have intensities of 1.0 - 1.5 mA. With either the former IUCF Atomic Beam (ABS) type polarized ion source (which is now at Dubna), or the reconstructed and improved ZGS/AGS ABS, we expect to obtain an intensity of about 1 mA. With 10% of the beam-time polarized, SeaQuest's 50 cm long H_2 target would have a time-averaged luminosity of about $2 \cdot 10^{35}$ cm^{-2} s^{-1}.
- The estimated total cost of the project is about \$4 Million (2012 dollars). The construction time could be about 2 years after approval and funding.

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1.1 SPIN@FERMI collaboration list

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1.2 Experimental Overview

M.A. Leonova, A.D. Krisch,

Introduction. The interest in spin phenomena has significantly increased in recent years. It is now clear that spin effects in high energy interactions provide essential information about the elementary particles' properties and structure. Recently, there has been significant progress in understanding the nucleon's longitudinal and transverse spin structure due to many polarization experiments done at SLC, HERA, CERN and RHIC. The Main Injector polarized proton beam would allow unique studies of spin phenomena such as the 1-spin asymmetry in all inclusive processes, including Drell-Yan and hadron and hyperon production. It would also allow both 1-spin and 2-spin asymmetry measurements of exclusive processes such as proton-proton elastic scattering at large $P_\perp^2$. Thus, the Main Injector's very high intensity could test the validity of strong interaction theories at the far larger $P_\perp^2$ values possible at 120-150 GeV/c.

Polarized Drell-Yan Experiments. The E-866[1] and E-906 (SeaQuest) collaborations have had a long-term interest in studying Drell-Yan processes with a 120-150 GeV/c polarized beam. Details are given in Section 1.4.

Polarized large $\mathbf{P_\perp^2}$ elastic and inclusive scattering. Transverse spin effects appear experimentally to increase at large-$P_\perp$. A high intensity polarized beam could determine if these unexpected spin effects persist at the larger $P_\perp$ possible at the 120-150 GeV/c Main Injector. The SPIN@FERMI Collaboration hopes to continue studying the proton's transverse spin structure by scattering a 120-150 GeV/c extracted polarized proton beam from a solid polarized proton target and a liquid hydrogen target. As shown in Fig. 1.1, a large left-right asymmetry A_N was found in polarized proton-proton elastic scattering at large $P_\perp^2$[2]. Currently, the nucleon's transverse spin structure is unexplored experimentally above about $P_\perp^2 = 7$ (GeV/c)^2.

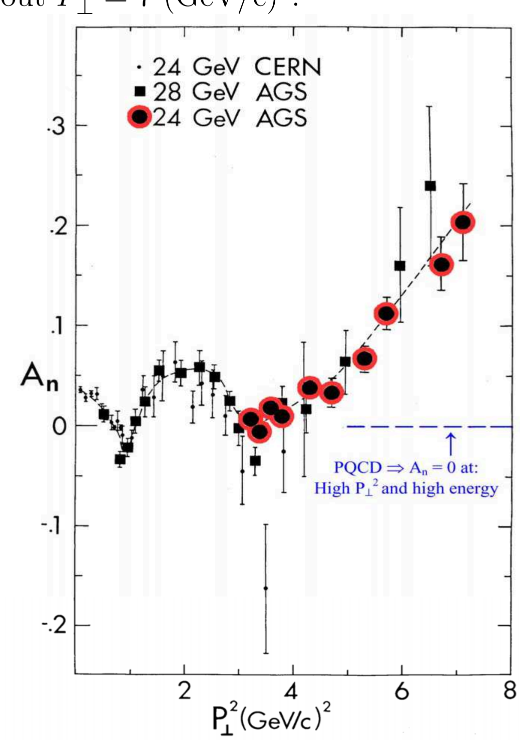

Figure 1.1: Plot of A_N against $P_\perp^2$ for proton-proton elastic scattering $(p_\uparrow + p \to p + p)$[2].

Similar large asymmetries were found in large-X_F inclusive pion production[3] from $P_{lab} = 12$ GeV/c to $s = 3900$ (GeV/c)^2, as shown in Fig. 1.2.

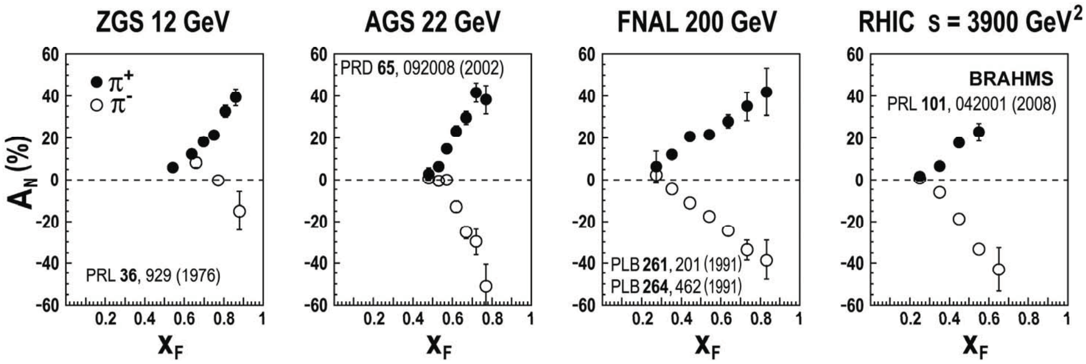

Figure 1.2: Inclusive 1-spin π^+ and π^- A_N (left-right asymmetry) plotted against X_F[3].

There are 2 independent 1-spin A_N asymmetries in large $P_\perp^2$ elastic scattering (polarized beam and polarized target),

$$p_\uparrow + p \to p + p \quad \text{and} \quad p + p_\uparrow \to p + p. \tag{1.1}$$

For identical particles, such as 2 protons, the 2 independent A_N asymmetries must be equal. These would be measured simultaneously with the 2-spin A_{NN} asymmetry,

$$p_\uparrow + p_\uparrow \to p + p. \tag{1.2}$$

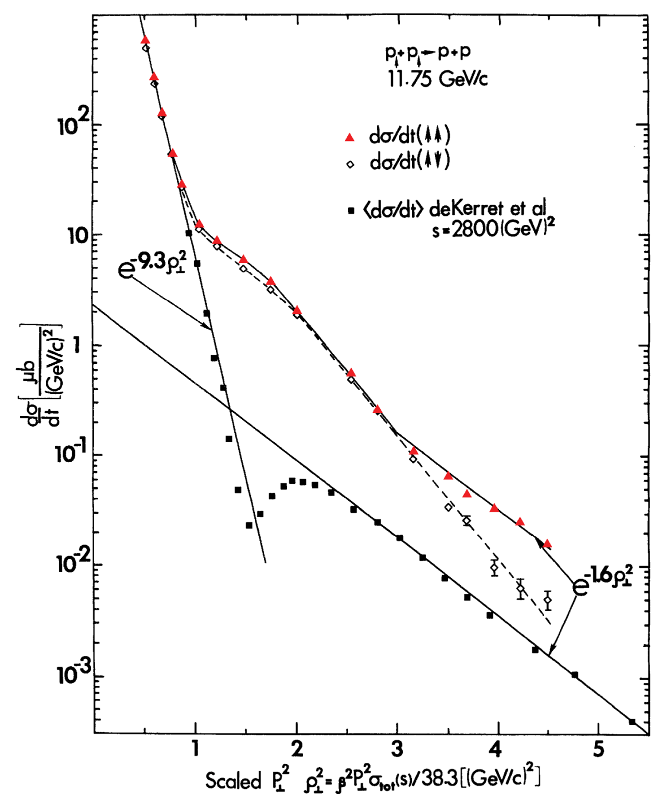

Figure 1.3: Spin-spin effects in 2-spin proton-proton elastic scattering at large $P_\perp^2$[4].

As shown in Fig. 1.3, a large and unexpected 2-spin asymmetry was found at large $P_\perp^2$ near 12 GeV/c. One could determine if the large and still unexplained A_{NN} disappears or persists at the large $P_\perp^2$ available at the high-intensity 120-150 GeV/c Main Injector.

Moreover, with the high intensity Main Injector, one could simultaneously measure the unpolarized proton-proton elastic cross section at large $P_\perp^2$ with much better precision than now exists. Figures 1.1, 1.3, 1.4 (and 1.6) show compilations of all existing data on the proton-proton elastic scattering's cross section and its A_N and A_{NN} asymmetries above a few GeV/c.

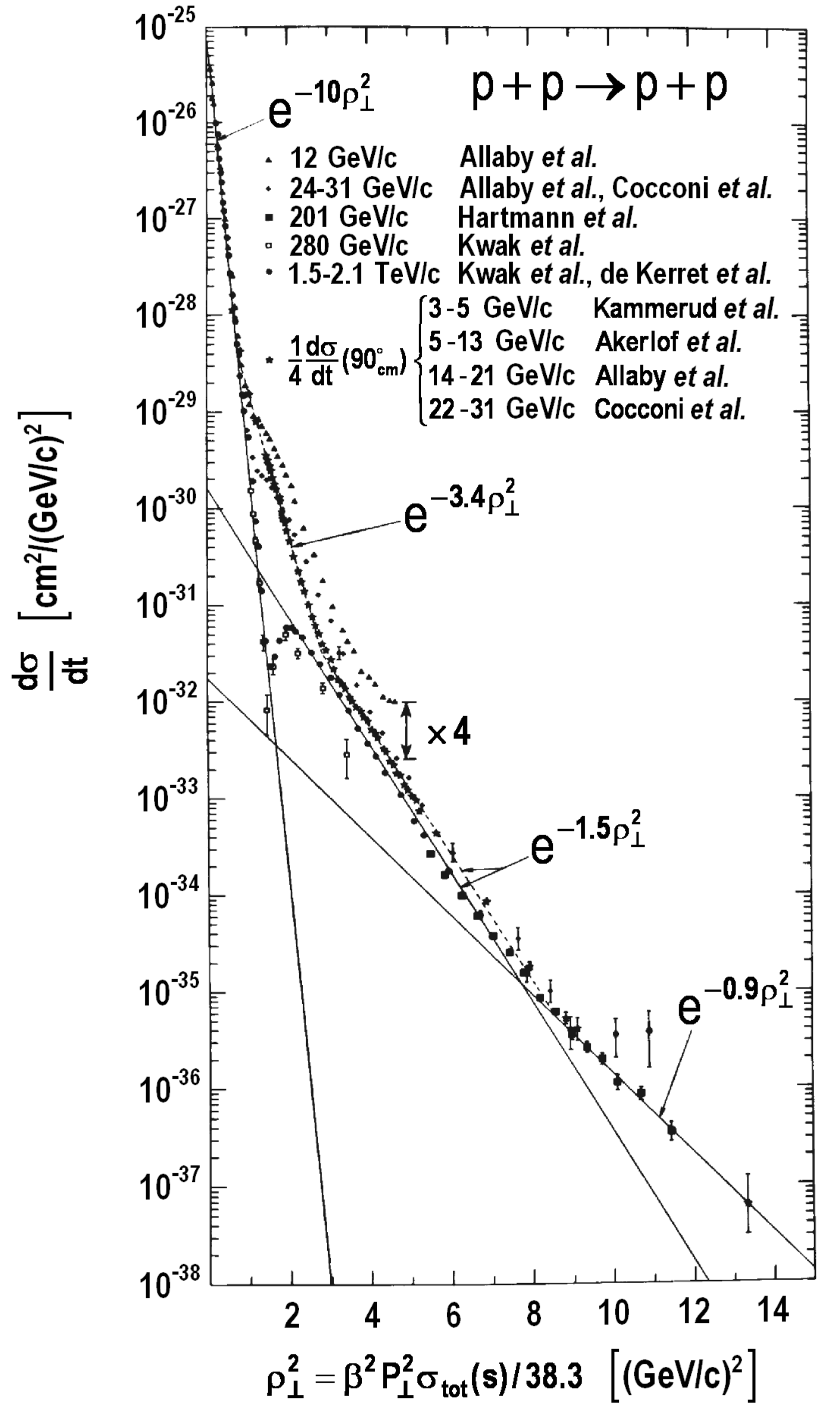

Figure 1.4: All unpolarized elastic proton-proton cross section data above 3 GeV/c plotted against the scaled $P_\perp^2$ variable[5].

1.3 Theoretical Overview

D.W. Sivers, M.A.Leonova, A.D. Krisch

Spin has been the quantum number that has mystified physicists since its publication by Uhlenbeck and Goudsmit in 1925[6]. Indeed, at the 1982 SPIN Symposium, C.N. Yang stated "I for one suspect that the spin and general relativity are deeply entangled in a subtle way that we do not understand"[7]. The modern spin era began with Wolfenstein's[8] efforts to develop a formalism to describe spin experiments, followed by the discovery by Oxley *et al.* of large spin effects at 200 MeV[9]. Fermi's last paper[10] focused on his amazement that the proton's spin, which had so little energy, was so important at 200 MeV. This paper resulted in his ex-student Chamberlain and others starting a series of double and triple scattering experiments and developing polarized proton targets and using them with unpolarized beams. Next, the development of the 12 GeV/c ZGS polarized proton beam allowed many precise spin experiments, such as proton-proton elastic scattering experiments[4, 11], which found unexpectedly large A_N and A_{NN} asymmetries at high $P_\perp^2$. This started the era of GeV polarized beams and polarized targets at many high energy and nuclear accelerators and colliders and many theoretical efforts to try to understand the resulting data.

There was a belief that quantum chromodynamics (QCD) predicted that all transverse single spin asymmetries would vanish at large transverse momentum. This misconception can be traced to statements found in the paper of Kane, Pumplin and Repko[12]. It correctly pointed out that large transverse single spin asymmetries are not generated in perturbative processes involving light quarks,

$$A_N\, d\sigma(qq_\uparrow \to qq)/d\sigma(qq \to qq) = \frac{\alpha_s(Q^2)}{Q} m_q f(\theta_{CM}). \tag{1.3}$$

But they mistakenly neglected other possible twist-3 mechanisms in a collinear factorization formulation of a hard scattering model, and used this to suggest the vanishing of 1-spin observables, such as A_N. During 1978-1988 this conclusion was widely accepted.

The correct interpretation[13] of their result was that, since perturbative processes involving light quarks do not themselves generate 1-spin asymmetries, they could be used to probe the asymmetries caused by the soft nonperturbative dynamics of QCD due to the interplay of confinement and dynamic chiral symmetry breaking. The asymmetries generated by such spin-orbit dynamics can be parameterized into k_T-dependent distribution functions (Sivers functions[13] or Boer-Mulders distributions[14]) or into k_T-dependent fragmentation functions (Collins functions[15] or polarizing fragmentation functions[13, 16]). They can also be parameterized into specific twist-3 operators in a collinear factorization approach. Mulders and his collaborators[16] classified the appropriate operators for 1-spin asymmetries but, mistakenly, called them T-odd suggesting that they violated time reversal invariance. In truth, the symmetry they violated involves a transformation related to the Hodge dual operator of differential geometry[17]. The Trento Conventions for transverse spin asymmetries are described in Ref[18]. The subject received a boost when Heppelmann, Collins and Ladinsky[19] noted that the quark transversity distributions, $\delta^T q(x)$, defined by Ralston and Soper[20] and renamed by Jaffe and Ji[21], could be measured in semi-inclusive deep inelastic scattering (SIDIS),

$$A_N\, d\sigma(lp_\uparrow \to l'\pi X) \propto \delta^T q(x) \otimes H_1(z). \tag{1.4}$$

Here $H_1(z)$ is the Collins function[15] that defines an asymmetry in the fragmentation of a transversely polarized quark. Asymmetries involving fragmentation functions can

be separated from those involving distributions in SIDIS and in the Drell Yan[22] process. In hadron-hadron collisions they can also be separated at the level of two-particle correlations in the final state. A comprehensive phenomenological fit to asymmetries in $e^+ + e^- \to hadrons$, semi-inclusive DIS and inclusive production in polarized hadron-hadron scattering, has been published by the Turin group[23]. They fit the transversity distributions for up and down quarks, favored and disfavored Collins functions, and orbital distributions for up and down quarks. This phenomenology is currently being extended to NLO in QCD perturbation theory. An important feature of "T-odd" distribution functions is that they are required to display a dramatic process dependence in order to be consistent with a gauge formulation of QCD. This result can be called Collins conjugation[24]. It needs to be tested. One comparison involves the measurement of orbital distributions (which are called Sivers functions) in DIS and in the DY process,

$$f_{1T}^{\perp q}(DIS) = -f_{1T}^{\perp q}(DY). \tag{1.5}$$

However, others can also be considered. In particular, the Boer-Mulders distributions exhibit the same process dependence as orbital distributions. Related processes involving associated baryon production can also be studied..

Exclusive processes in QCD involve local descriptions in terms of, so called, generalized parton distributions (GPD's) and effective field theories incorporating constraints generated by crossing and analyticity. Quantum chromodynamics predicts that elastic transverse spin asymmetries for hadron-hadron scattering at large transverse momenta involve a combination of the Chou-Yang[25] mechanism involving orbital angular momentum and the Brodsky-Lepage[26] effective field theory which involves truncation of the Fock states combined with power-law approximations to effective form factors. However, the data shown in Figs. 1.1, 1.2 and 1.3 are too small a set of data to conclusively filter the various theoretical approaches. Its range needs to be increased. High intensity 120-150 GeV/c polarized proton beams from the Main Injector could allow a comprehensive experimental program of transverse single-spin and double-spin experiments.

Single-Spin Asymmetries

These studies take advantage of the high luminosity possible with a polarized beam scattering on an unpolarized target, together with the flexibility of incorporating high-resolution measurements of momentum with particle identification in fixed-target experiments. A list of important experiments would include:

1. Polarized Drell Yan asymmetries

$$A_N \, d\sigma(p_\uparrow + p \to \mu^+ + \mu^- + anything) \tag{1.6}$$

This is a fundamental measurement that can be used to test the validity of the gauge formulation of QCD in regions where the fundamental degrees of freedom cannot be clearly isolated. In this sense, Collins conjugation can be formulated in analogy to the Bohm-Aharanov test of the gauge formulation of QED.

2. Spin asymmetries in Baryon production

$$A_N\, d\sigma(p_\uparrow + p \to B + anything) \tag{1.7}$$

These asymmetries involve mechanisms closely related to those responsible for the production of baryons with polarization (P) from unpolarized scattering processes.

$$Pd\sigma(p + p \to B_\uparrow + anything) \tag{1.8}$$

Inclusive hyperon polarization [Eq. (1.8)] was studied experimentally in the late 1970s at Fermilab[27].

3. Elastic Scattering Single Spin Asymmetries

$$A_N\, d\sigma_{el}(p_\uparrow + p \to p + p) \tag{1.9}$$

This could test the combination of the Brodsky-Lepage[26] effective field theory with the Chou-Yang[25] formulation of elastic scattering involving orbiting constituents. It provides an independent measurement of the mean orbital angular momentum of the rotating charges.

4. Spin asymmetries in inclusive pseudoscalar and vector meson production

$$\begin{gathered} A_N\, d\sigma(p_\uparrow + p \to M + anything), \\ \text{where} \quad M = \pi, K, \eta, \eta', \rho, K^\star, \omega, \phi. \end{gathered} \tag{1.10}$$

These processes were studied experimentally in the late 1980s at Fermilab[28]. Much higher intensity studies could provide a more precise understanding of Collins functions and precision measurements of orbital distributions.

5. Two-particle correlations

$$A_N\, d\sigma(p_\uparrow + p \to \phi^+ + \phi^- + anything) \tag{1.11}$$

Non-resonant two-particle correlations can be used to distinguish between asymmetries that occur in the fragmentation process (Collins functions) from those that occur in the proton's distribution orbital distributions (Sivers functions). These experiments take advantage of the ability to combine accurate momentum measurements with particle identification in fixed target experiments.

6. Spin asymmetries in inclusive J/ψ, ψ' and Charm production

$$A_N\, d\sigma(p_\uparrow + p \to J/\psi + anything);\; A_N\, d\sigma(p_\uparrow + p \to \psi' + anything) \tag{1.12}$$

Like the Drell Yan process, these processes are free from important fragmentation asymmetries and can be used to measure gluon orbital distribution functions and, hence, gluon orbital angular momentum. Again, the access to forward kinematics is an immense advantage of fixed target kinematics.

Double-Spin Asymmetries

Combining a polarized beam with a polarized target provides access to two spin asymmetries. Here we only mention a few transverse A_{NN} asymmetries, which could be studied experimentally using a Main Injector polarized beam:

1. Drell-Yan 2-Spin Experiment

$$A_{NN}\, d\sigma(p_\uparrow + p_\uparrow \to \mu^+ + \mu^- + anything) \tag{1.13}$$

There is a strong prejudice that antiquark transversities are very small, but this belief needs to be confronted with experiment. In addition, there are many other asymmetries involving different angular distributions that appear with the extra degree of freedom.

2. High-$\mathbf{P_\perp^2}$ 2-Spin proton-proton elastic Experiment

$$A_{NN}\, d\sigma_{elastic}(p_\uparrow + p_\uparrow \to p + p) \tag{1.14}$$

Extending these experiments[4, 11] to the $P_\perp^2$ available at the Main Injector would provide a tremendous expansion of the range in which the Brodsky-Lepage[26] approach to exclusive processes has been measured.

1.4 Physics with 120-150 GeV/c polarized beams

W. Lorenzon, A.D. Krisch

A 120-150 GeV polarized beam at the Fermilab Main Injector and a liquid hydrogen target and/or a solid polarized proton target (PPT) could allow a wide range of 1-spin and 2-spin asymmetry measurements. Particularly interesting would be: Drell-Yan[22] scattering experiments with a transversely polarized protons beam on unpolarized liquid hydrogen targets; and large-$P_\perp^2$ elastic scattering in view of the still unexplained huge transverse spin-effects at 12 to 28 GeV/c found at the ZGS[29] and AGS[30]. Some transversely polarized hadron measurements include:

- the Sivers asymmetries in high precision polarized Drell-Yan experiments;
- the 1-spin A_N and 2-spin A_{NN} in large-$P_\perp^2$ proton-proton elastic scattering;
- the 2-spin proton-proton total cross section $\sigma_{tot}A_{NN}$;
- the 2-spin D_{NN} of Λ-hyperon polarization via its self-analyzing decay;
- the left-right asymmetry in Σ^0-production or ρ-production;
- the left-right asymmetries in inclusive pion and kaon production.

1. Polarized Drell-Yan scattering has become a major milestone in the hadronic physics community, motivated by a fundamental prediction of QCD that postulates a sign change in the Sivers function[13] measured in Drell-Yan scattering as compared to semi-inclusive deep inelastic scattering (SIDIS)[24, 31]. Each quark and antiquark flavor has its own Sivers function described by a transverse-momentum dependent distribution function that captures non-perturbative spin-orbit effects inside a polarized proton. The experimental verification of the sign change goes to the heart of the gauge formulation of QCD and would fundamentally test the factorization approach to the description of processes sensitive to transverse parton momenta. It would be crucial to confirm the validity of our present conceptual framework for analyzing hard hadronic reactions.

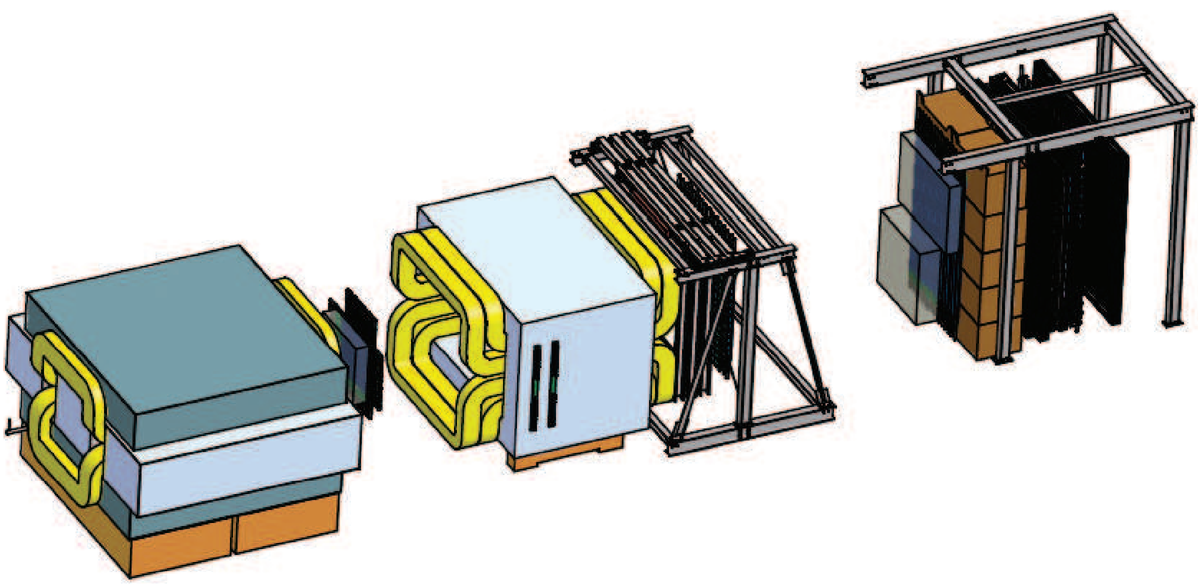

Figure 1.5: Schematic layout of the polarized Drell-Yan spectrometer. The polarized beam enters from the left and hits a 50-cm long unpolarized target before it is stopped in the 5-m long solid-iron magnet.

The HERMES[32] and COMPASS[33] experiments have measured single transverse spin asymmetries and performed global fits to the Sivers asymmetries with high precision. In order to make a meaningful comparison of shape and sign, comparable measurements are needed for single spin asymmetries in the Drell-Yan process. While many experiments around the globe aim to measure polarized Drell-Yan either with a polarized beam or a polarized target, none of them is optimized for Drell-Yan except for the SeaQuest dimuon spectrometer at the Fermilab Main Injector. SeaQuest will use 5-s long spills of $2 \cdot 10^{12}$ protons/s each minute ($\mathrm{I_{av}} = 1.6 \cdot 10^{11}$ protons/s) on a 50-cm long liquid hydrogen (or deuterium) target ($N_p = 2.1 \cdot 10^{24}$ cm^{-2}). This results in an average luminosity of $3.4 \cdot 10^{35}$ cm^{-2}s^{-1} and a total integrated beam of $3.4 \cdot 10^{18}$ protons on target over a period of 2 to 3 years of running.

The big attraction for a polarized Drell-Yan program at the Fermilab Main Injector is a spectrometer and hydrogen target that are well-understood, fully functioning, and optimized for Drell-Yan at the end of data collection for the SeaQuest experiment, shown in Fig. 1.5. Based on the study presented in this report and experience from current polarized ion sources, it is expected that an ion source that produces 1 mA at the source can deliver up to 150 nA (about $1 \cdot 10^{12}$ p/s) to the experiment by using 30 two-second cycles and slip stacking into the Main Injector. Assuming that 50% of the total beam time is allocated to the experiment, a luminosity of $1 \cdot 10^{36}$ cm^{-2}s^{-1} can be obtained. It is important to note that even if only 10% of the available beam time was allocated to the experiment, a luminosity of $2.0 \cdot 10^{35}$ cm^{-2}s^{-1} is still very competitive. In addition, the SeaQuest spectrometer accommodates a large coverage in x, i.e., $x_1 = 0.3 - 0.9$ covering the valence quark region, and $x_2 = 0.1 - 0.5$ covering the sea quark region. While the Sivers function can be measured for both the valence quarks or the sea quarks, sea quark effects might be small due to competing processes, while valence quark effects are generally expected to be large[34]. Thus, using a polarized beam might have a substantial advantage over a polarized target. The combination of high luminosity, large x-coverage and a high-intensity polarized beam makes Fermilab arguably the best place to measure Drell-Yan scattering with high precision.

2. Polarized elastic scattering could shed new light on the nature of the strong interaction. As discussed in the attached March 1992 Polarized Main Injector Report, one could do many fixed-target elastic polarized beam experiments with very high luminosity. These 120-150 GeV/c experiments could use the existing Michigan solid Polarized Proton Target (PPT) which operated at the AGS with a time-averaged beam intensity of over 10^{11} protons/s and polarization of about 85%. With a 10% time share available for polarized beam, the expected 120-150 GeV/c polarized beam intensity of $\sim 1 \cdot 10^{12}$ protons per Main Injector cycle, would give an average beam intensity of $\sim 1 \cdot 10^{11}$ protons/s scattering from this solid polarized target ($N_p = 2 \cdot 10^{23}$ cm^{-2}); the proton-proton luminosity would be about

$$\mathcal{L} = 2 \cdot 10^{34}\ cm^{-2}\ s^{-1}\ . \tag{1.15}$$

A high quality recoil proton spectrometer could simultaneously extend the range of A_N, A_{NN} and the elastic cross section in the unexplored large-$P_\perp^2$ region shown in Figs. 1.1, 1.3 and 1.6, and Fig. 1.4, respectively. A possible placement for the solid PPT and a large-$P_\perp^2$ elastic recoil spectrometer in the Meson Hall is shown in Fig. 1.7. Moreover, the experiment was originally proposed for the 400 GeV/c UNK where the non-elastic

background was considerably larger; thus, the recoil spectrometer might be significantly shortened to fit better into the Meson Hall, as was done in the U-70 Hall, after UNK was suspended. These experiments could run simultaneously with the Main Injector running in the polarized and unpolarized mode on interspersed pulses. These 120-150 GeV/c fixed-target spin experiments may provide further justification for developing polarization capability at Fermilab. The SPIN@FERMI collaboration has been very interested in 120-150 GeV/c large-$P_\perp^2$ elastic proton-proton spin experiments since the 1980s.

The luminosity of $\sim 2 \cdot 10^{34}$ cm^{-2} s^{-1} should be adequate for elastic scattering out to $P_\perp^2$ of $\sim$12 (GeV/c)^2. The expected polarized elastic event rates per day are about:

$$\begin{aligned}
200000 \text{ at } P_\perp^2 &= 2 \text{ (GeV/c)}^2;\\
40000 \text{ at } P_\perp^2 &= 4 \text{ (GeV/c)}^2;\\
4100 \text{ at } P_\perp^2 &= 6 \text{ (GeV/c)}^2;\\
480 \text{ at } P_\perp^2 &= 8 \text{ (GeV/c)}^2;\\
80 \text{ at } P_\perp^2 &= 10 \text{ (GeV/c)}^2;\\
20 \text{ at } P_\perp^2 &= 12 \text{ (GeV/c)}^2.
\end{aligned}$$

We might later increase these event rates by:

- increasing the polarized ion source intensity above 1.5 mA;
- further improving the PPT for running with high beam intensity.

3. Polarized Large-$\mathbf{P_\perp}$ inclusive processes. Measuring inclusive spin effects at the high-intensity Main Injector could provide a precise new probe of the strong interaction at very large $P_\perp$. One could precisely measure, at very large $P_\perp$, the 1-spin transverse asymmetries (A_N) in inclusive processes such as:

$$p_\uparrow + p \to \pi^\pm + anything, \tag{1.16}$$

$$p_\uparrow + p \to K^\pm + anything. \tag{1.17}$$

Fig. 1.8 shows the unpolarized inclusive jet data from the D0 and CDF detectors[35]. These data indicate that jets and thus probably pions, kaons and antiprotons could be precisely measured, with high accuracy, at the maximum $P_\perp^2$ of 54 (GeV/c)^2 available at 120 GeV/c and 67 (GeV/c)^2 at 150 GeV/c. Unfortunately, it is very difficult to measure the 2-spin inclusive A_{NN} from a solid polarized proton target (PPT) due to the unpolarized protons and neutrons in the NH_3 target's beads, and in the PPT's helium coolant and bead container. However, it is straightforward to measure 1-spin inclusive asymmetries (A_N) from a liquid hydrogen target.

Note that by adding two simple threshold Cherenkov counters to the elastic recoil spectrometer shown in Fig. 1.7, one could precisely measure inclusive cross sections, as was done in 1967-69 at the ZGS[36] and in 1971 at the ISR[37]. Since the inclusive pion, kaon and antiproton production cross sections at large $P_\perp^2$ are far larger than the elastic cross sections one could make rather precise A_N measurements, even at $P_\perp^2$ of 50-70 (GeV/c)^2. Then, the prediction that for inclusive processes $A_N = 0$ at large $P_\perp^2$ could be definitively tested with high precision.

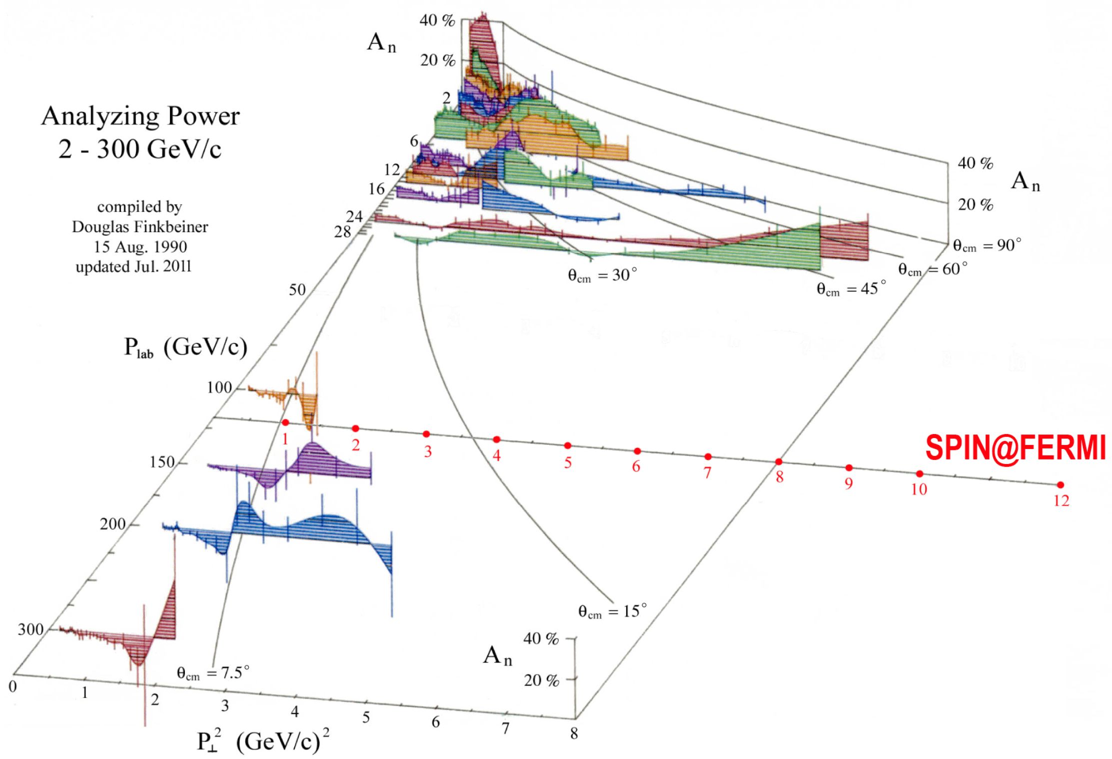

Figure 1.6: Compilation of all elastic A_N data above 2 GeV/c showing range of possible SPIN@FERMI experiment.

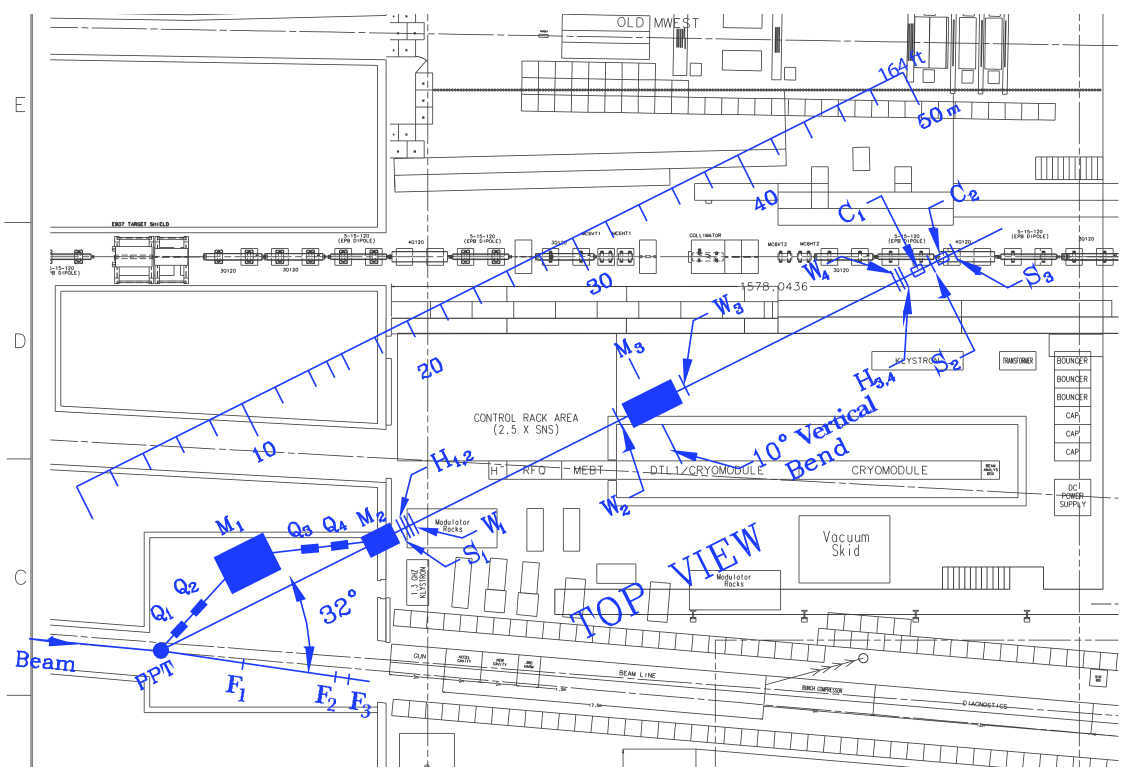

Figure 1.7: Possible SPIN@FERMI experiment layout in the Meson Hall.

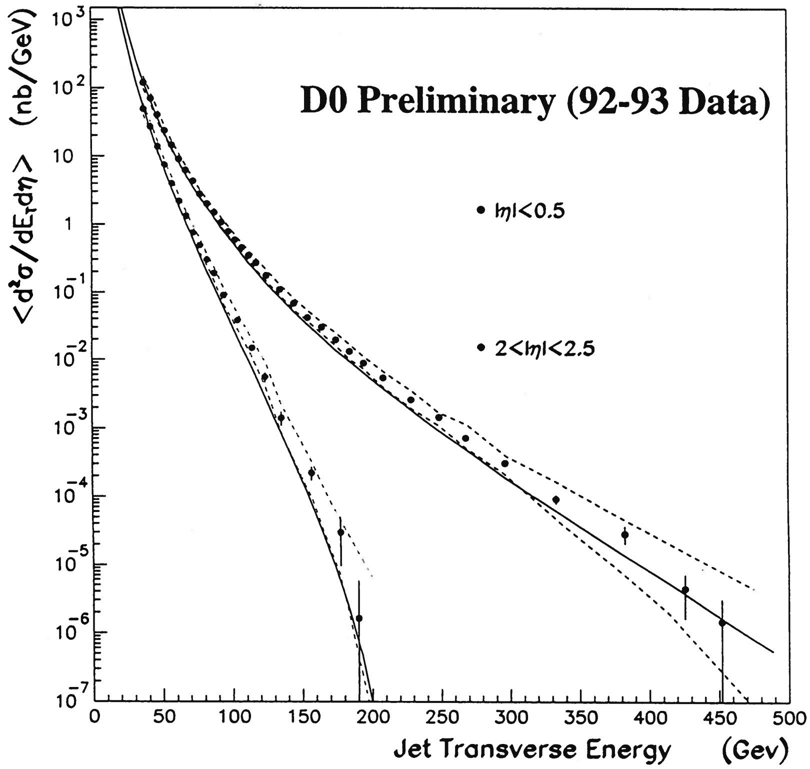

Figure 1.8: Inclusive jet cross-section plotted against transverse energy[35].

4. Polarized Total Cross Sections. The Main Injector polarized beam could allow extending the 2-spin transverse proton-proton total cross section $\sigma_{tot}A_{NN}$ measurements to 120-150 GeV/c. One could use the traditional beam absorbtion technique with circular scintillators of decreasing radius followed by extrapolation of their measured rates back to zero radius. This simple measurement[38] was the first polarized beam experiment when the polarized ZGS beam first operated in 1973. Measuring σ_{tot} is far easier in fixed target experiments than in collider experiments.

1.5 Updated Summary of Polarized Beam Acceleration

M.A. Leonova, R.S. Raymond, A.D. Krisch

To accelerate polarized protons in the Main Injector, changes are needed in most Fermilab accelerator stages as shown in Fig. 1.9. Some of these changes were discussed in the attached 1992 Polarized Main Injector Report[39]; however, much of the information is now out of date. The "searchable" attached 1995 Report[40], whose relevant sections are listed below, contains many more details, which could help one to follow this brief Updated Report.

- Section 3 p.49 Polarized Beam Intensity
- Section 4 p.53 Polarized Proton Accumulation in Recycler Ring
- Section 5 p.55 High Intensity Polarized H^- Source
- Section 6 p.67 RFQ for polarized H^-
- Section 7 p.85 Low Energy Beam Transport
- Section 8 p.91 Booster Resonance Correction
- Section 9 p.107 Main Injector Siberian Snakes
- Section 12 p.147 Polarimeters
- Section 14 p.181 Spin Rotation in Transport Lines
- Section 15 p.187 Computer Controls and Interfaces

The major new items or changes needed are shown below and summarized in this Updated Report, where we discuss polarized beam acceleration in the current Main Injector.

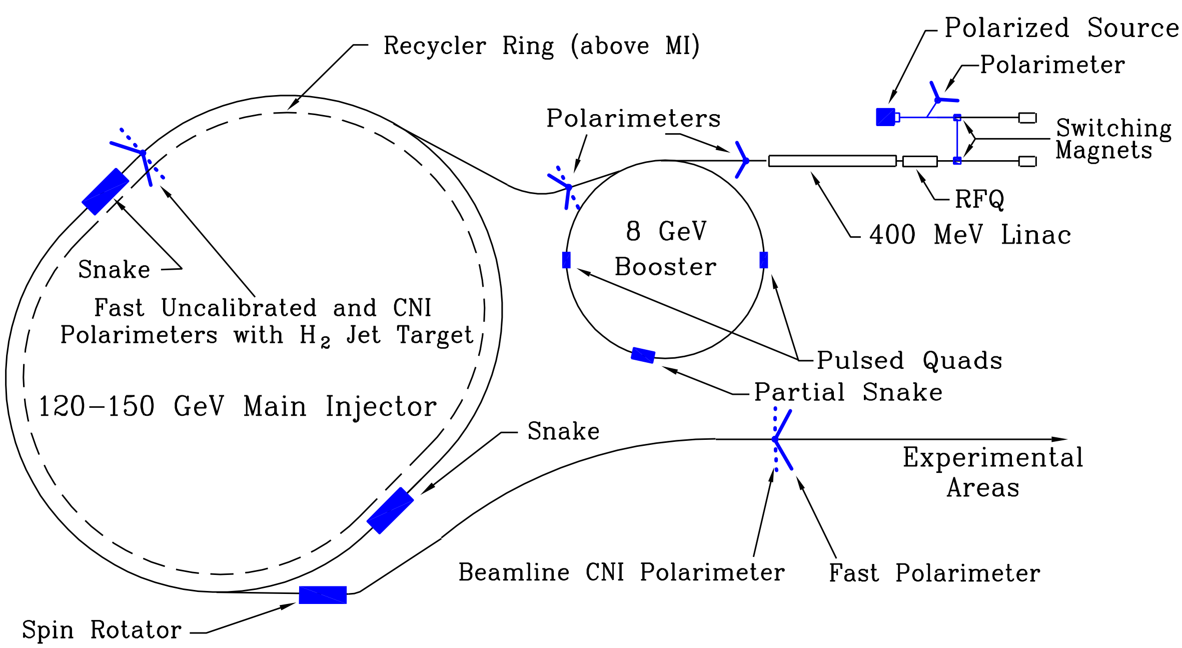

Figure 1.9: Major items needed for polarized beam at Fermilab.

Accelerator Modifications

1. Polarized Ion Source: Polarized ion sources now have intensities of 1.0 - 1.5 mA[41, 42]. Either the former IUCF Atomic Beam type (ABS) polarized ion source (which is now at Dubna), or the reconstructed and improved ZGS/AGS ABS, could provide $\sim$1 mA.

2. Beam Transport Line from 35 keV Polarized Source to RFQ: Polarized source could share Fermilab's new RFQ with unpolarized sources by using new bending magnets to switch between sources each cycle. No depolarization if all bends are horizontal.

3. RFQ: No depolarization in an RFQ; no changes are needed.

4. Beam Transport Line from 750 keV RFQ to LINAC: No changes are needed.

5. 35 keV & 400 MeV Polarimeters: A 35 keV RHIC-type polarimeter could monitor the source polarization during unpolarized cycles. A 400 MeV beam-line polarimeter with a $\sim$0.5 mm carbon target could monitor polarized cycles with $\sim$1% beam loss.

6. Beam Stacking and Intensity: No changes are needed.

7. 400 MeV LINAC: There is no depolarization in LINACs; no changes are needed.

8. 400 MeV Transport Line: Depolarization is only 0.2%; no changes needed.

9. 8.9 GeV/c Booster Partial Siberian Snake: A warm 4% partial solenoidal snake, using the Booster power supply to oscillate at 15 Hz with a Max $\int B \cdot dl \sim 1.33\ T \cdot m$ at 8.9 GeV/c, should overcome all 15 imperfection resonances (See p. 22). One could compensate small betatron-tune shift by properly ramping ring quadrupoles. [*The AGS may have a used similar magnet.*] [*Weak corrector dipoles might instead overcome the rather weak imperfection resonances while improving the Booster beam alignment.*]

10. 8.9 GeV/c Booster Pulsed Quadrupoles: Two pulsed quadrupoles (3 - 10 μs risetime) should overcome the one fairly weak intrinsic resonance.

11. 8.9 GeV/c Transport Line Polarimeters: Fast relative and CNI calibrated polarimeters, sharing a Carbon or fishline target, could measure the relative polarization after each polarized $\sim$67 ms Booster cycle.

12. 8.9 GeV/c Transport Lines: The Booster-RR line has intermingled horizontal and vertical bends; rotator NEEDS MORE STUDY. No depolarization in RR-MI line.

13. 8.9 GeV/c Recycler Ring: Operating point far from any resonance (See p. 22).

14. 120-150 GeV/c Main Injector Siberian Snakes: Two superconducting Siberian snakes in Main Injector should maintain $\sim$95% of injected polarization. The snakes must be on opposite sides of MI with orthogonal spin rotation axes. The snake orbit excursions must fit inside the snake magnets' ID at 8.9 GeV/c injection.

15. 120-150 GeV/c Polarimeters: Relative and CNI polarimeters in the 120-150 GeV/c transport line sharing a $\sim$0.3 mm carbon or fishline target could measure the beam polarization during polarized cycles with $\sim$3% beam loss. The fast polarimeter could be calibrated against the CNI polarimeter, and/or the Polarized Proton Target by measuring simultaneously elastic A_N from the beam and target (Eq. 1.1). [*Internal polarimeters may be possible with a very-fast-pulsed-valve hydrogen jet target.*]

16. 120-150 GeV/c Transport Line Spin Rotators: A superconducting 60° spin rotator may be needed to correct for the spin rotation due to the intermingled horizontal and vertical bends in the transfer line. NEEDS MORE STUDY.

17. Computer Controls and Interfaces: Controls for all polarized beam hardware must be interfaced with main accelerator control computer.

Procedure for accelerating polarized protons

SeaQuest might prefer two 3-second or three 2-second polarized cycles per minute. However, it might be most practical to switch from unpolarized to polarized cycles for one minute once every ten minutes. This would also give the polarized beam 10% of the beam-time and the unpolarized beam 90%. Its most important advantage over switching once per minute, is that it would reduce the switching frequency tenfold and allow far slower switching times for the switching magnets before the RFQ and most importantly much slower time for switching the polarimeter targets in and out of the beams. Going from 50 ms to perhaps 1 s would significantly increase the switching hardware's lifetime and reduce its cost. It would also reduce the targets' oscillations after each switch, which was a significant problem in recent experiments at COSY[43]. The 2 seconds of switching time could be charged to the polarized beam time.

The following should be done to tune the polarized beam (once after each shut-down):

a. Turn on the polarized H^- ion source and measure the polarization at the 35 keV Lamb-Shift Polarimeter. Tune the polarized source to maximize the polarization.
b. Adjust the switching magnet to inject polarized rather than unpolarized H^- ions into the main low energy beam transport (LEBT) line to the RFQ and LINAC.
c. Measure the polarization at 400 MeV with a carbon-target polarimeter.
d. Turn on the Booster partial snake and adjust its ramp and the timing of the pulsed quadrupoles to maximize the polarization measured by the 8.9 GeV/c transport line polarimeters.
e. Turn on the two Main Injector snakes and measure the polarization in the two Main Injector internal (or possibly extracted beam) polarimeters. Adjust the snake currents together to maximize the polarization. [The two cold superconducting Main Injector Snakes stay ON during both polarized and unpolarized cycles.]
f. Adjust for slow extraction into the spin experimental area rather than fast extraction into the neutrino production line.
g. Adjust the spin rotator in the 120-150 GeV transport line to give the proper spin direction in the spin experimental area. Measure the extracted polarization using a beam line polarimeter.
h. Record the magnets' settings into a separate file for a polarized beam cycle..

The following would be done during operation for switching between polarized and unpolarized cycles:

a. Adjust the switching magnet to inject polarized ions into the main LEBT line to the RFQ.
b. Load the cycle settings for a polarized beam (with a snake ramp and quadrupole pulse in the Booster, and a flat-top in the Main Injector with slow extraction into the spin experimental area).
c. Set 400 MeV and 8.9 GeV polarimeter targets to switch into beam only on polarized cycles, if needed.
d. Adjust the switching magnet to inject unpolarized ions into the main LEBT line to the RFQ.
e. Load the cycle settings for an unpolarized beam.

1.6 Summary of Needed Polarized Hardware

1. **Polarized Ion Source**
   The source should produce a high intensity $H^-_\uparrow$ ion beam using Belov-type[41] Deuterium charge exchange from a ground state type $H^\circ_\uparrow$ atomic beam stage.
   Intensity: 1.0 mA
   Pulse Length: $40 - 100$ μs
   Polarization: more than 75%
   Emittance: 1.5 π mm-mrad
   Output Energy: 35 keV
   Pulse Frequency: 15 Hz
   Production Time: $12 - 24$ months
   Remarks: This is a specialized high maintenance device; Fermilab staff should be integrated early into the $H^-_\uparrow$ source program.
   Estimated Cost: ∼\$600,000

2. **Beam Transport line from 35 keV polarized source to the RFQ.**
   Normalized Emittance: 0.3 π mm-mrad
   Vacuum: $\sim 10^{-7}$ Torr
   Hardware: Vacuum Pipe and Vacuum Pumps
   Focusing Quadrupoles and Einzel lenses
   Bunchers (1 or 2)
   Switching Magnet (1-3 Hz between $H^-_\uparrow$ line and unpolarized lines)
   Building Modification Time: ∼3 months; Estimated Cost: ∼\$100,000
   Production Time: ∼12 months
   Estimated Cost: ∼\$100,000

3. **RFQ**
   The radio frequency quadrupole preaccelerator (with power supply) should accelerate 35 keV ions to the LINAC acceptance energy.
   Energy: 35 keV to 750 keV
   Frequency: 201.25 MHz
   Ion Type: polarized H^-
   Transmission Efficiency: ∼98%
   Maximum Current: 50 mA
   Cavity length: 163 cm
   Minimum radius: 2.6 mm
   Normalized Emmittance: 0.3 π mm-mrad
   Intervane RF Voltage: 67 kV
   RF Power: 100 kW
   Production Time: ∼12 or 0 months
   Estimated Cost: ∼\$400,000 or \$0

4. **Beam Transport line from 750 keV RFQ to LINAC.**
   Production Time: No change needed.
   Estimated Cost: \$0

5. **35 keV and 400 MeV Polarimeters**
   These polarimeters could measure the transport-line polarization before the RFQ and after the LINAC.
   Energy and Type:
   35 keV: Lamb-shift (kills beam; use during unpolarized cycles);
   400 MeV: p + C $\rightarrow$ p + C (kills $\sim$1% of beam)
   Detectors:
   35 keV: Quench in strong E-field; measure Lyman-α photons;
   400 MeV: Scintillators
   Polarization Measurement Accuracy:
   35 keV: $\sim$2% in $\sim$ 10 sec;
   400 MeV: $\sim$2% in $\sim$1 min
   Production Time: $\sim$12 months
   Estimated Costs: 35 keV: $\sim$\$ 100,000; 400 MeV: $\sim$\$100,000
6. **Beam Stacking and Intensity**
   One could use something like the unpolarized stacking procedure for polarized ions: 40 μs pulses at 15 Hz repetition rate going into the LINAC and injected into the Booster for 12 turns; then 6 Booster pulses injected into the Recycler Ring followed by 6 more pulses using "slip-stacking"; then injection into the Main Injector ring.
   Energy: 400 MeV injection into Booster; 8.9 GeV/c stacking in RR and MI.
   Polarized Booster Pulse Intensity Estimate:
   (46-turn-injection) 1.0 mA $\times$ **100** μs $\times$ $6.24 \cdot 10^{18}$ protons/C = $6.2 \cdot 10^{11}$ protons;
   (18-turn-injection) 1.0 mA $\times$ **40** μs $\times$ $6.24 \cdot 10^{18}$ protons/C = $2.5 \cdot 10^{11}$ protons;
   (12-turn-injection) 1.0 mA $\times$ **26** μs $\times$ $6.24 \cdot 10^{18}$ protons/C = $1.66 \cdot 10^{11}$ protons.
   MI Pulse Intensity Estimate ($2 \times 6 = 12$ Booster Pulses and $\sim$95% transf. effic.):
   with **100** μs source pulse: $7 \cdot 10^{12}$ protons;
   with **40** μs source pulse: $2.8 \cdot 10^{12}$ protons;
   with **26** μs source pulse: $1.9 \cdot 10^{12}$ protons.
   With 10% polarized-beam-time, one could optimize the instantaneous and average intensities by varying the polarized pulses' duration, frequency, and sequencing:
   a. with **100** μs source pulse: nineteen 3-sec pulses every 10^{th} minute with flat-top of $3 - 1.5 = 1.5$ sec and slow extraction time of 1.5 sec giving instantaneous intensity of $\mathbf{4.7}\cdot 10^{12}$ p/sec and average intensity $\mathbf{13}\cdot 10^{12}$ p/min.
   b. with **26** μs source pulse: two 3-sec pulses every minute with flat-top of $3-1.334 = 1.666$ sec and slow extraction time of 1.66 sec giving instantaneous intensity of $\mathbf{1.1}\cdot 10^{12}$ p/sec and average intensity $\mathbf{3.8}\cdot 10^{12}$ p/min.
   c. with **26** μs source pulse: three 2-sec pulses every minute with flat-top of $2-1.334 = 0.666$ sec and slow extraction time of 0.66 sec giving instantaneous intensity of $\mathbf{2.9}\cdot 10^{12}$ p/sec and average intensity $\mathbf{5.7}\cdot 10^{12}$ p/min.

   No changes needed. Estimated Cost: $\sim$\$0
7. **400 MeV LINAC**
   There is no depolarization in LINACs; no changes needed. Estimated Cost: $\sim$\$0
8. **400 MeV Transport Line**
   Depolarization is only 0.2%; no changes needed. Estimated Cost: $\sim$\$0

9. **8.9 GeV/c Booster Partial Siberian Snake**
   A ramped warm solenoid 4% partial snake should overcome all 15 imperfection depolarizing resonances at $G\gamma = 3$ to 17 (See p.22). Try to run at $\nu_y = 6.7$.
   Energy/Momentum: 400 MeV to 8.9 GeV/c
   Magnetic Field Integral: sine wave with amplitude increasing from 0.14 to 1.33 T·m
   Ampere Turns: 10^6 maximum
   Maximum Current Density: 823 A/cm^2
   Coil Dimensions: Inner Rad: 4.6 cm; Outer Rad: 16.3 cm; Length: 156 cm
   Wire Dimensions: 12 mm × 12 mm with 5 mm diam water path
   1080 turns (9 layers × 20 turns)
   Solenoid Parameters: L ∼20 mH; R ∼110 mΩ
   Power Supply: Booster Power supply provides current ramped at 15 Hz into a special solenoid circuit with C ∼8.5 mF;
   Peak Voltage ∼1 kV; Average Power ∼45 kW
   Production Time: ∼12 months [*The AGS may have a used similar magnet.*]
   Estimated Cost: ∼$200,000
10. **8.9 GeV/c Booster Pulsed Quadrupoles**
    Two pulsed quadrupoles (with ceramic vacuum chambers and a power supply) could jump the Booster's intrinsic depolarizing resonance ($G\gamma = 0 + \nu_y$) near $\gamma = 3.79$. One could use or modify 2 of the **15** AGS Pulsed Quadrupoles (built by Michigan) and possibly 1 or 2 of their power supplies (built by Brookhaven).
    Energy: T = 2.56 GeV (P = 3.36 GeV/c)
    Risetime: 3 μs (300 μs falltime)
    Tune shift: $\nu_y = 0.2$
    Field Gradient: 1.38 $T \cdot m^{-1}$
    Geometry: 3.5 cm inside radius × 50 cm long
    Inductance: 5 μH
    Power Supply: 4.3 kV, 1.3 kA for both quadrupoles
    Production Time: ∼12 months
    Estimated Cost: ∼$100,000
11. **8.9 GeV/c Transport Line Polarimeter**
    Fast relative and calibrated CNI polarimeters could measure the beam polarization after each ∼67 ms Booster acceleration cycle using p-Carbon and p-p elastic and quasielastic asymmetries and CNI asymmetries, respectively (see Item 15).
    Energy/Momentum: 8.9 GeV/c
    Target: Probably moving CH_2 fishline or carbon fiber
    Detector: Scintillators
    Polarization Measurement Accuracy: ∼3% in 4 mins
    Production Time: ∼12 months
    Estimated Cost: ∼ $200,000
12. **8.9 GeV/c Transport Lines** NEEDS MORE STUDY
    No depolarization in RR-Main Injector line. Booster-RR line has intermingled horizontal and vertical bends; needs spin Rotator. Estimated Cost: ∼$100,000

13. **8.9 GeV/c Recycler Ring**
No hardware changes are needed, but one should change the RR's ν_y to better avoid the $G\gamma = 24 - \nu_y$ intrinsic resonance, which is near the RR's fixed γ of 9.536. The nearby $G\gamma = 17$ imperfection resonance at $\gamma = 9.483$ may be a problem that NEEDS MORE STUDY. Estimated Cost: $0

Table 1.1: Fermilab Booster depolarizing resonances.[40]

ν_s	γ	T (GeV)	ϵ
3	1.673	0.631	0.00010
4	2.231	1.155	0.00014
5	2.789	1.678	0.00026
6	3.347	2.201	0.00110
7	3.905	2.725	0.00180
8	4.462	3.247	0.00048
9	5.020	3.771	0.00005
10	5.578	4.294	0.00013
11	6.136	4.818	0.00027
12	6.694	5.341	0.00022
13	7.251	5.863	0.00040
14	7.809	6.387	0.00042
15	8.367	6.910	0.00030
16	8.925	7.434	0.00206
17	9.483	7.957	0.01010
K=0 + ν_y	3.781	2.549	0.0132
K=24 - ν_y	9.611	8.064	0.0474

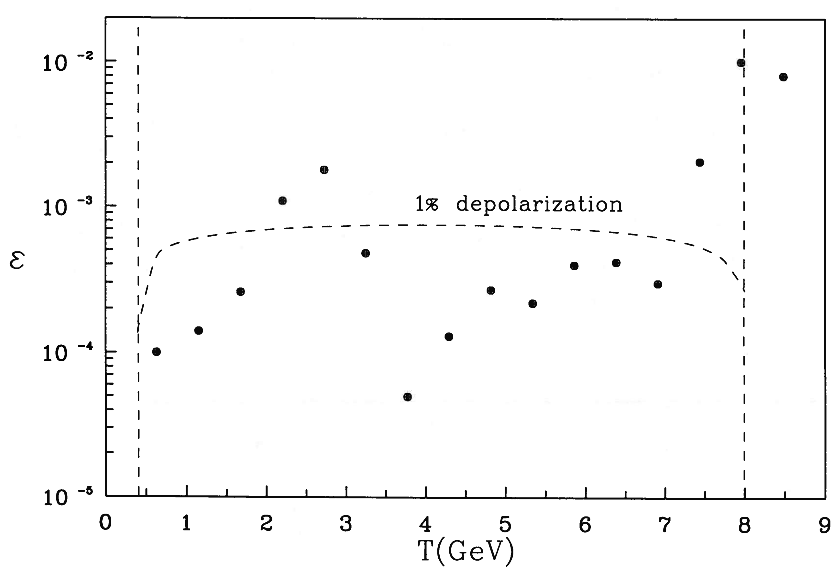

Figure 1.10: Booster imperfection depolarizing resonance strengths and 1% depolarization line.[40]

14. **120-150 GeV/c Main Injector Superconducting Siberian Snakes**
Two Siberian snakes[44, 45, 46] each containing 4 superconducting transverse DC helical dipole magnets could overcome all depolarizing resonances in the Main Injector by rotating the spin by 180° about a horizontal 45° axis. The two snakes must be placed on exactly opposite sides of the Main Injector ring, probably in the MI-30 and MI-60 straight sections. Moreover, to overcome strong depolarizing resonances the spin rotation axes of the two snakes must be orthogonal; for example, their axes could be +45° and −45° from longitudinal. Note that since they are superconducting, one must certify the Main Injector tunnel for cryogenic liquids.

We have come up with 2 different snake designs which are described below. Both are based on the clever and efficient RHIC 4-helical dipole design[47, 48], where all 4 helices are of equal lengths, with the inner pair of helices at equal high B-fields and the outer pair at equal lower B-fields. Moreover, each of the 4 dipoles has the same 360° helical rotation. Our new design[49] is based on modifying the RHIC design by making the inner pair shorter than the outer pair, so that the up and down vertical beam excursions are exactly equal. This minimizes the inside diameter of the snakes and thus significantly reduces their cost. These two new snake designs seem quite interesting. The snakes are fairly short with rather small orbit excursions, as discussed below. The 6" ID / B_{max} = 5 T snakes would require less time and R&D; they have the same ID as the Main Injector; thus, they seem best from some points of view. However, the 4" ID / B_{max} = 8 T snakes would be shorter, and space for a snake in MI-60 may be an issue. Moreover, it could serve as an inexpensive pilot project for using superconducting NiSn magnets in high energy accelerators with a factor of ∼2000 less NiSn cable than the 27 km LHC.

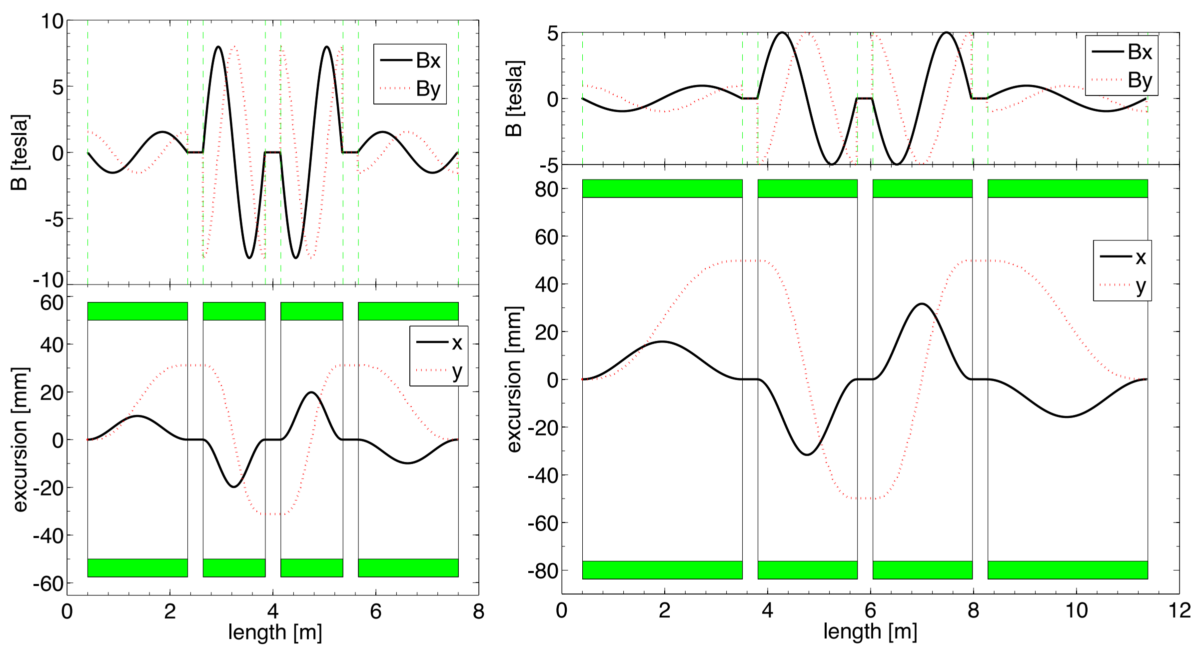

Figure 1.11: Snakes with (LEFT) 4" ID and B_{max} = 8 T and (RIGHT) 6" ID and B_{max} = 5 T.

Two Possible Siberian Snake Designs

Description	6" ID and B_{max} = 5 T	4" ID and B_{max} = 8 T
Spin Rotation Axis	45°	45°
Number of Helical Dipoles	4	4
Helical Dipole's Lengths	3.108 m (2) & 1.934 m (2)	1.943 m (2) & 1.548 m (2)
Total Snake Length	11.6 m	7.8 m
B_{max}	5 T	8 T
Max Hor Excursion	31.7 mm	19.8 mm
Max Vert Excursion	49.8 mm	31.2 mm
Magnet Aperture	6" ID (152 mm ID)	4" ID (100 mm ID)

Momentum: 8.9 GeV/c to 120-150 GeV/c
Production Time: 24 months
Estimated Cost: $600,000 (based on RHIC snake cost)

15. **120-150 GeV/c Transport-Line & Possibly Internal Polarimeters**
Two transport-line polarimeters pointed at one target could measure the beam polarization after each polarized MI acceleration cycle. One polarimeter should be fast but only relatively calibrated for beam tuning. The other polarimeter could be slow but should be absolutely calibrated. A fast relative and a CNI polarimeter in the 120-150 GeV/c transport line sharing a ∼0.2 mm carbon or fishline target could measure the beam polarization after each polarized cycle with ∼2% beam loss. The fast polarimeter could be calibrated against the CNI polarimeter, [*and/or the Polarized Proton Target by measuring simultaneously the elastic A_N from the beam and target (See Eq. 1.1)*]. The Coulomb Nuclear Interference (CNI) polarimeter would measure the left-right asymmetry in proton-proton elastic scattering in the CNI region[50] [$P_\perp^2$ ∼0.003 $(GeV/c)^2$] using very small recoil hodoscopes very near 90°_{lab}. The Fast polarimeter could use 2 small scintillator arms to detect p-Carbon and p-p elastic and quasielastic scattering. [*Internal fast and CNI polarimeters may be possible with very-fast-valve-pulsed hydrogen jet target.*]
Production Time: ∼12 months
Estimated Cost: ∼$200,000 transport line + ∼$200,000 internal

16. **120-150 GeV/c Transport Line Spin Rotator** NEEDS MORE STUDY
There is significant spin rotation (perhaps 60°)in the MI to experimental areas transfer lines. This could be compensated by a cold helical spin rotator in the 120-150 GeV/c transfer line. The rotator would be somewhat similar to the eight 90° rotators in RHIC.
Production Time: ∼24 months
Estimated Cost: ∼$300,000 (based on RHIC rotator cost)

17. **Computer Controls and Interfaces**
Controls for all polarized beam hardware must be conveniently and reliably interfaced with the main accelerator control computer.
Production Time: ∼12 months
Estimated Cost: ∼$200,000

1.7 Hardware Instalation and Schedule

The below schedule assumes that:

1. the funding decision for this polarized beam project is made by December 2011;
2. the IUCF polarized source now at Dubna will be available;
3. Brookhaven will help to build the superconducting snakes and rotator;
4. the switching magnets and vacuum pipes for the polarized source will be installed along with the RFQ;
5. the used AGS partial snake and pulsed quadrupole are available;
6. the ion source area (or some nearby area) is accessible during MI running.

Then one could install some of the necessary hardware during the presently planned FY 2012 Main Injector upgrade period. As shown in Fig. 1.12, about 2 years seems an appropriate time for the polarized beam engineering design and fabrication.
A possible commissioning sequence is:

a. The polarized ion source is a critical path item. It should be obtained promptly if Dubna agrees to sell or lease the former IUCF source. Then it could be installed and commissioned during the long shutdown. [*If not, the reconstructed ZGS/AGS polarized source might be ready by late 2013. Then it could be installed and commissioned during the 2014 summer shutdown.*]

b. The polarized source's 35 keV transport lines, and the source switching magnets should be fabricated and installed along with the RFQ.

c. The 35 keV polarimeter could then be installed and commissioned along with the polarized source.

d. The 400 MeV, 8.9 GeV/c and hopefully two 120-150 GeV/c polarimeters could be fabricated by early 2013. Then they could be installed and commissioned during the 2013 Summer shutdown.

e. The Booster's partial snake and fast tune-jumping quadrupoles should be obtained promptly. They could then be installed during the long shutdown. Then there could be Booster polarized beam studies, involving injection, acceleration, and extraction during the 2013 Summer shutdown.

f. The superconducting Siberian snakes and 60° rotator are the second critical path item. They should be obtained promptly if Brookhaven agrees to fabricate them. Then they could be installed and commissioned during the 2014 Summer shutdown.

g. During late 2014 polarized protons could be injected into the Main Injector for commissioning in the 10% of beam-time mode.

1.8 Commissioning

The Fermilab polarized beam commissioning might be somewhat similar to the AGS polarized beam commissioning[30], where the polarized proton source, the 750 keV RFQ and the 200 MeV LINAC were first tuned using a 200 MeV polarimeter. The polarized 200 MeV LINAC beam was then transported to the AGS and accelerated. In the Fermilab Booster, the partial snake should prevent depolarization by the imperfection resonances and the fast tune shifting quads should overcome the intrinsic depolarizing resonances. We expect to maintain the full source polarization of 75%-80% during acceleration in the Booster and transport to the Main Injector. We would then measure the Main Injector polarization during and after acceleration and may tune its Siberian snakes if necessary. We may also adjust the Main Injector orbits, tunes, and chromaticity to maintain good emittance, intensity, and polarization. Polarized beam would then be extracted and transported to the experimental areas; the beam transport line rotators would then be tuned. This item NEEDS MORE STUDY.

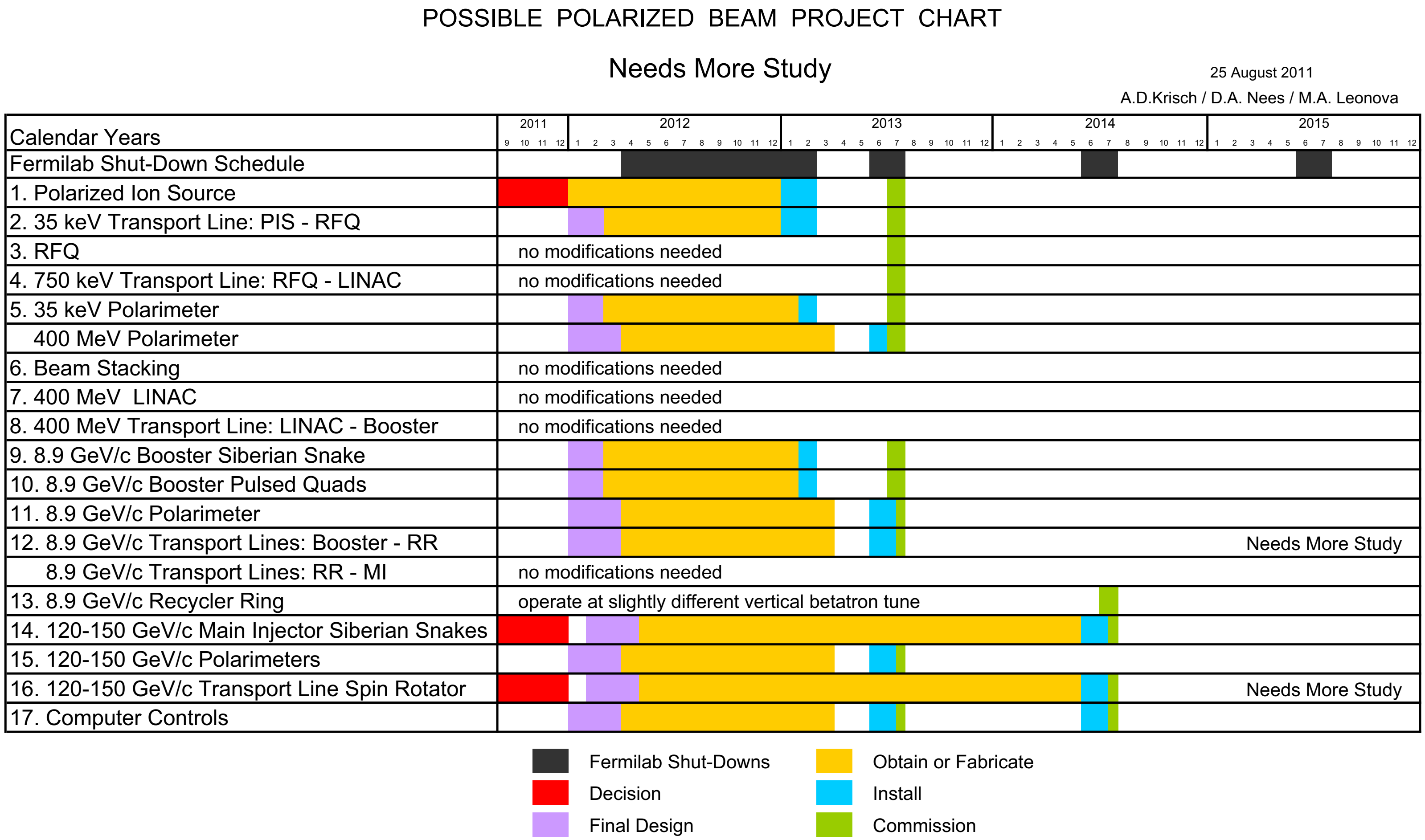

Figure 1.12: Possible Project Chart.

1.9 Estimated Budget

Preaccelerator		$0.9M
Polarized H^- ion source	$0.6M	
35 keV polarimeter	$0.1M	
RFQ and power supply (35 keV to 750 keV)	$0.0M	
Beam lines, switching magnets & vacuum system	$0.1M	
Building Modification	$0.1M	
400 MeV LINAC		$0.1M
400 MeV polarimeter	$0.1M	
8.9 GeV/c Booster		$0.6M
Solenoid partial Siberian snake (ramped warm)	$0.2M	
Two 3 μsec pulsed quadrupoles with power supplies	$0.1M	
8.9 GeV/c polarimeter	$0.2M	
8.9 GeV/c transfer line spin rotator	$0.1M	
Main Injector		$0.9M
Two Helical Siberian snakes	$0.6M	
Power supplies for snakes	$0.1M	
120-150 GeV/c polarimeters (CNI & Inclusive)	$0.2M	
120-150 GeV/c Transfer Line		$0.5M
120-150 GeV/c polarimeters (CNI & Inclusive)	$0.2M	
120-150 GeV/c transfer line spin rotator	$0.3M	
Miscellaneous		$0.2M
Computers, control modules, cables, and interface	$0.2M	
Main Injector subtotal		$3.2M
Contingency (∼25%)		$0.8M
MAIN INJECTOR TOTAL		**∼$4M**

The estimate for the total cost of obtaining 120-150 GeV/c polarized proton beam capability at Fermilab is given in 2012 Dollars.

1.10 Summary

With a 50 cm long liquid hydrogen target and 10% of the beam time, the time-averaged polarized beam luminosity for the Main Injector could probably be about $2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$ or higher. This polarized luminosity should allow precise measurements of spin-asymmetries out to $P_\perp^2$ of 50-70 (GeV/c)^2 for inclusive hadron production. The world's highest intensity polarized proton beam with a 50 cm hydrogen target would also allow precise studies of polarized Drell-Yan processes. With a solid polarized proton target, it could also allow high-precision 1-spin, 2-spin and spin-averaged studies of violent elastic proton-proton collisions out to $P_\perp^2$ of at least 12 (GeV/c)^2 - a fundamental probe of the strong interaction.

The total cost of providing a 120-150 GeV/c polarized proton beam could be about $4 Million and the time needed for producing the needed hardware could be about 24 months from the time of approval and funding.

References

[1] J.M. Moss *et al.*, Draft Letter of Intent, 10 May 1995.

[2] P.R. Cameron *et al.*, Phys. Rev. Rapid Comm. **D32**, 3070 (1985);
D.G. Crabb *et al.*, Phys. Rev. Lett. **64**, 2627 (1990).

[3] C.A. Aidala, *Proc. of 18th Int. Spin Physics Symposium*, AIP **1149**, 124 (2009);
D.G. Crabb on behalf of SPIN08 organizing committee, CERN Courier June (2009).

[4] J.R. O'Fallon *et al.*, Phys. Rev. Lett. **39**, 733 (1977);
D.G. Crabb *et al.*, Phys. Rev. Lett. **41**, 1257 (1978).

[5] A.D. Krisch, Phys. Rev. Lett. **19**, 1149 (1967);
P.H. Hansen and A.D. Krisch, Phys. Rev. **D15**, 3287 (1977);
A.D. Krisch, Z. Phys. **C46**, S113 (1990).

[6] G.E. Uhlenbeck and S. Goudsmit, Naturwiss. **13**, 953 (1925).

[7] C.N. Yang, AIP Conf. Proc. **95**, 1 AIP, New York (1983).

[8] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949);
L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952).

[9] C.L Oxley *et al.*, Phys. Rev. **93**, 806 (1954).

[10] E. Fermi, Il Nuovo Cimento **93**, 11 (1954).

[11] E.A. Crosbie *et al.*, Phys Rev. **D23**, 600 (1981).

[12] G. Kane, J. Pumplin and W. Repko, Phys. Rev. Lett. **41**, 1689 (1978).

[13] D.W. Sivers, Phys. Rev. **D41**, 83 (1990); **D43**, 261 (1991).

[14] D. Boer and P.J. Mulders, Phys. Rev. **D57**, 5780 (1998).

[15] J.C. Collins, Nucl. Phys. **B396**, 161 (1993).

[16] R.D. Tangerman and P.J. Mulders, Phys Rev. **D51**, 3357 (1995); Nucl. Phys. **B461**, 197 (1996).

[17] D.W. Sivers, Phys Rev. **D74**, 094008 (2006).

[18] A. Bacchetta, U. D'Alesio, M. Diehl and C.A. Miller, Phys Rev. **D74**, 094008 (2006).

[19] J.C. Collins, S.F. Heppelmann and G.A. Ladinsky, Nucl. Phys. **B420**, 565 (1994).

[20] J.P. Ralston and D.E. Soper, Nucl. Phys. **B152**, 109 (1979).

[21] R.L. Jaffe, X.-D. Ji, Phys. Rev. Lett. **67**, 552 (1991).

[22] S.D. Drell and T.-M. Yan, Phys. Rev. Lett. **25**, 316 (1970).

[23] M. Anselmino *et al.*, Nucl. Phys. Proc. Suppl. **91**, 98 (2009), arXiv:0812.4366[hep-ph].

[24] J.C. Collins, Phys. Lett. **B536**, 43 (2002), arXiv:hep-ph/0204004.

[25] T.T. Chou and C.N. Yang, Phys. Lett. **135**, 175 (1984).

[26] G.P. Lepage and S.J. Brodsky, Phys. Rev. **D22**, 2157 (1980).

[27] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976);
K. Heller *et al.*, Phys. Rev. **D16**, 2731 (1977).

[28] A. Yokosawa et al.,Phys. Lett. **B261**, 201 (1991); Phys. Lett. **B264**, 462 (1991).

[29] T. Khoe *et al.*, Part. Accel **6**, 213 (1975).

[30] F.Z. Khiari *et al.*, Phys. Rev., **D39**, 45 (1989).

[31] S.J. Brodsky *et al.*, Nucl. Phys. **B642**, 344 (2002), arXiv:hep-ph/0206259.

[32] A. Airapetian, *et al.*, (HERMES Collaboration), Phys. Rev. Lett. **94**, 012002 (2005), arXiv:hep-ex/0408013.

[33] V.Y. Alexakhin, *et al.*, (COMPASS Collaboration), Phys. Rev. Lett. **94**, 202002 (2005), arXiv:hep-ex/0503002.

[34] M. Anselmino *et al.*, EPJA. **39**, 89 (2009).

[35] H. Weerts, private communications.

[36] L.G. Ratner *et al.*, Phys. Rev. Lett **18**, 1218 (1967);
L.G. Ratner *et al.*, Phys. Rev. **166**, 1353 (1968);
G.J. Marmer *et al.*, Phys. Rev. Lett. **23**, 1469 (1969).

[37] L.G. Ratner *et al.*, Phys. Rev. Lett. **27**, 68 (1971).

[38] E.F. Parker *et al.*, Phys. Rev. Lett. **31**, 783 (1973);
W. de Boer *et al.*, Phys. Rev. Lett. **34**, 558 (1975).

[39] *Report on Acceleration of Polarized Protons to 120 and 150 GeV in the Fermilab Main Injector*, SPIN Collaboration, Unpublished University of Michigan Report UM HE 92-05 (March 1992).

[40] *Report on Acceleration of Polarized Protons to 120 GeV and 1 TeV at Fermilab*, SPIN Collaboration, Unpublished University of Michigan Report UM HE 95-09 (July 1995).

[41] A.S. Belov *et al.*, private communications.

[42] A.N. Zelenski *et al.*, SPIN 2008.

[43] V.S. Morozov *et al.*, Phys. Rev. Lett. **103**, 144801 (2009);
V.S. Morozov *et al.*, Phys. Rev. Lett. **102**, 244801 (2009);
V.S. Morozov *et al.*, Phys. Rev. Lett. **100**, 054801 (2008).

[44] Ya.S. Derbenev and A. M. Kondratenko, Sov. Phys. JETP 35, 230 (1972);
Ya.S. Derbenev *et al.*, Part. Accel 8, 115 (1978).

[45] *Proc. of 1985 Ann Arbor Workshop on Polarized Beams at SSC*, eds. A.D. Krisch, A.M.T. Lin and O. Chamberlain, AIP Conf. Proc. **145** (AIP, New York 1986).

[46] A.D. Krisch *et al.*, Phys. Rev. Lett. **63**, 1137 (1989).

[47] M. Syphers *et al.*, *Proc. of 1977 Part. Accel. Conf.*, 3359 (1998);
E. Willen, *et al.*, *Proc. of 1999 Part. Accel. Conf.*, 3161 (1999);
E. Willen, *et al.*, *Proc. of 2003 Part. Accel. Conf.*, 164 (2003).

[48] E. Willen, *et al.*, *Proc. of 2005 Part. Accel. Conf.*, 2935 (2005).

[49] M.A. Leonova, E.D. Courant and A.D. Krisch, in preparation.

[50] J. Schwinger Phys. Rev. **73**, 407 (1948).